

NASA/TM—2015-218752

AIAA—2014-3672



ADDJUST—A View of the First 25 Years

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May 2015

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Prepared for the
50th Joint Propulsion Conference
cosponsored by the AIAA, ASME, SAE, and ASEE
Cleveland, Ohio, July 28–30, 2014

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Space Administration

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Acknowledgments

The authors would like to thank and acknowledge the extraordinary contributions of Mr. Daniel Swanson and his exemplary team at General Dynamics, and of Mr. Jack Estes of NASA Lewis. Without Dan's expertise in trajectory design and Jack's experience in wind data interpretation and loads calculations, I seriously doubt that ADDJUST could have been developed.

Level of Review: This material has been technically reviewed by technical management.

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ADDJUST—A View of the First 25 Years

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Abstract

Various technologies and innovative launch operations were developed during the 50 years of the Centaur upper stage—the first launch vehicle to use high performing liquid hydrogen fuel. One innovation was “ADDJUST”, which enabled the successful negotiation of upper level winds measured only hours before launch. Initial causes for its creation, development, and operation during countdown are detailed. Problem definition, wind measuring/monitoring process, pitch and yaw steering coefficient generation, loads analysis, angle of attack, major risks/concerns, and anecdotal recollections are provided. Launch availability improved from as low as 55 to 95 percent due to ADDJUST, which is still in use.

Nomenclature

P	pitch
Y	yaw
h	height
Δ	change
θ	steering angle

1.0 Introduction

This paper recounts my personal experiences with the history of Atlas/Centaur’s progression of techniques over the years to deal with safe flight through the upper level winds. As a retired NASA engineer after 35 years on the Centaur project at NASA Lewis (later renamed Glenn), I share my recollections on the problems we had and the solutions we adopted. In many cases, original charts were used for historical authenticity when they were available. ADDJUST is the acronym for Automatic Determination and Dissemination of Just Uppdated Steering Terms. The acronym is attributed to Mr. Frank Anthony of General Dynamics, Convair division, which manufactured the Atlas and Centaur stages for Lewis in San Diego. ADDJUST is the automated computer and communication system used to provide Atlas/Centaur and, later, Titan IIIE/Centaur, with open loop, booster phase steering data on launch day. It still flies

today on Centaur as the upper stage for Atlas V. The first paper published on ADDJUST was written by Daniel C. Swanson of General Dynamics, Convair Division, in 1976 (Ref. 1). While Swanson expertly recounted the technical aspects of ADDJUST in that brief paper (also presented in some detail here), this paper also provides a historical view of ADDJUST, with perspectives unique to NASA. Reference 1 described ADDJUST results only up to the mid-1970s time frame, where this paper discusses results through 1998. Some materials are originally from an unpublished presentation co-authored by the first author (Ref. 2) No attempt was made to discuss the modern United Launch Alliance (ULA) implementation of ADDJUST on the current Atlas V launch vehicle.

The Centaur upper stage was first flown successfully in 1963. The launch of an early Atlas/Centaur (AC) configuration is shown in Figure 1. Centaur was initially developed as an upper stage for the Atlas booster to fly the Surveyor lunar soft lander missions beginning in 1966. It later flew on Titan IIIE/Centaur as well. Centaur is best known for becoming the first upper stage to use liquid hydrogen as a fuel. But it also pioneered the development of other technologies, including an innovative approach to successfully negotiate upper level winds. That approach was called ADDJUST. This paper addresses my recollections of its development, how it worked, why it was so critically needed, and its performance through the late 1990s. In 1998 the Centaur program was transferred from Lewis to Kennedy Space Center, Florida. Major risks and mitigations are discussed.

NASA Lewis Research Center directed General Dynamics (GD), to develop the ADDJUST system for Atlas/Centaur in 1972, following a series of costly launch aborts due to upper level flight wind restrictions. Requirements for ADDJUST development were to automate existing computer programs on GD’s scientific computer in San Diego, to interface the system with existing flight wind restriction procedures, to communicate results to Lewis for independent verification and validation (IV&V) and to the launch complexes, with minimum impact on launch operations. ADDJUST was to provide for rapid design, trajectory/performance validation, and transfer of wind-biased pitch and yaw steering terms. It was required to

* Retired

respond to data from balloon soundings released from the Eastern Test Range (ETR) about 2.5 hr before liftoff. The Atlas/Centaur target launch availability (statistical probability of launching through the flight winds, see Sec. 4.1) was set at 90 percent for the worst winter months, compared to the existing 55 percent with techniques then in use. The decision to launch Centaur would be made only after all Mission Acceptance Criteria (see Sec. 4.4) were met, based on prelaunch GD calculations independently verified by Lewis.

2.0 Background

A typical flight profile for Atlas/Centaur is shown in Figure 2 (Ref. 3) Atlas and Titan boosters accelerated the Centaur upper stage through the atmosphere. Steering commands during the booster phase were computed by Centaur, using constants that were remotely loaded during the prelaunch countdown. Flight guidance was broken up into an open loop booster phase and a closed loop, exoatmospheric phase. The ADDJUST system provided the wind-biased steering data used only in the open loop phase of booster flight. Most loads that will occur in flight can be calculated well in advance of the launch date (see Sec. 4.5). One effect, however, that of prevailing, variable, upper level atmospheric wind conditions, must be accounted for just prior to launch in order to maximize the probability of launching through these winds. The wind loads were reduced in flight by using biased booster phase pitch and yaw steering programs that compensated for winds aloft by reducing the vehicle's angle of attack in the critical regimes where high dynamic pressures were encountered. Prior to ADDJUST, a set of pitch and yaw programs based on synthetic or seasonal mean winds was provided and stored in a preprogrammed "library" in the Centaur ground computer at Launch Complex 36. A rapid search procedure was employed to select the best combination of these pitch and yaw programs to minimize the wind loads and meet all the Mission Acceptance Criteria. This combination of prestored programs was then loaded into the Centaur flight computer. The entire library of programs had been verified many weeks before launch.

But starting with AC-30 in 1973, after the Centaur had experienced a series of costly launch scrubs because of unacceptably high predicted flight wind loads, it was decided that pitch and yaw steering programs had to be specifically designed and tailored to the launch day measured wind. These steering programs would then be uploaded to the Centaur computer shortly before launch. The tasks of designing these programs, verifying

that the loads and all other critical Mission Acceptance Criteria were met, and reliably transmitting the programs from San Diego to the vehicle ground computer on the pad in Florida were under control of a computer program called ADDJUST. Typically, these programs were then uploaded into the Centaur flight computer within about 20 min of launch (sometimes much less). These rapid transmissions were made possible by the development of computer remote terminal equipment with supporting hardware and software which allowed large scale, home based scientific computers to be used in near real time applications. These capabilities allowed multi-stage design, analysis, validation and error free communications programs required for ADDJUST to be linked together and controlled by remote terminals. Inputs to and outputs from a computer were exchanged with remote site computers using ordinary, voice band telephone circuits. The predicted results provided the basis for a GO/NO-GO recommendation.



Figure 1.—Early Atlas/Centaur Launch

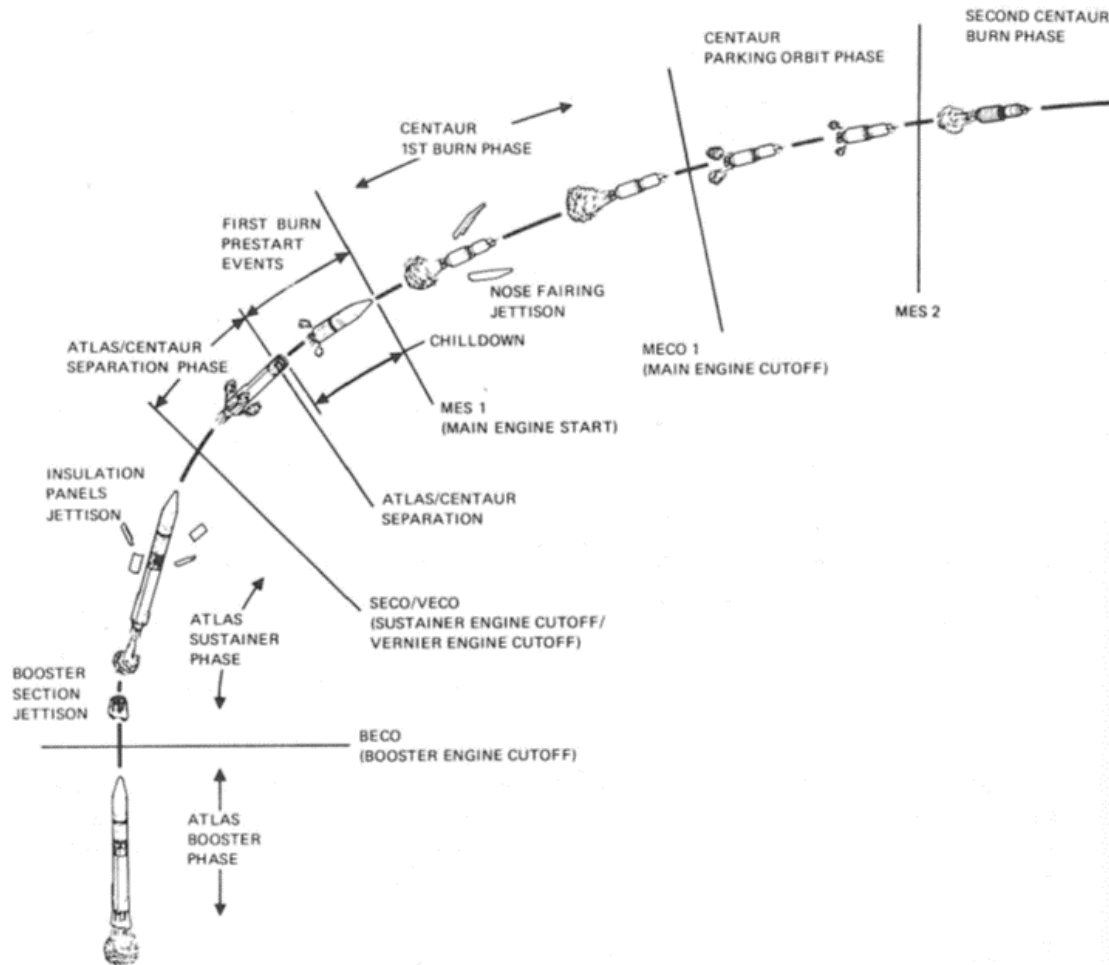


Figure 2.—Typical Flight Profile of Atlas/Centaur

3.0 Brief History

In the early to mid-1960s, Centaur used four preprogrammed pitch profiles, one for each season. Each profile was a set of open loop pitch rate versus time commands. Initially, we flew nine launches without scrubbing for winds, i.e., one of those programs resulted in acceptable mission criteria, notably structural loading. (Even in the early 1970s, scrubs cost about 1 million dollars per day). Over time, since Centaur was always under pressure to increase its payload capability, we lengthened the Atlas tank and increased the booster thrust, so we became more susceptible to wind loads. Eventually we evolved to a 10 x 10 matrix of programs, now both pitch and yaw, to minimize weather-related scrubs. These expanded choices worked quite well into the early 1970s, until we scrubbed the launch of AC-25 in 1971, for our first commercial customer, Intelsat. We then expanded the matrix again, this time to include 10,000 pitch and yaw combinations, first used on AC-27 in 1972, the first launch of a Pioneer

spacecraft to Jupiter. With so many choices, we felt that we could surely find a combination that would work. Table 1 contains a summary of the evolution of the booster steering programs.

As I recall we only had a dozen or so possible launch days for AC-27 and we scrubbed for winds the first three of them, causing significant concern. We successfully launched on the fourth day, to the great relief of all. But for the first three days, we had not been able to find a combination that worked, as we then realized that the problem was that we just couldn't search through 10,000 combinations in a timely fashion. After AC-27 launched, our Center Director, Mr. Bruce Lundin, came up to me in a restaurant in Cocoa Beach, Florida, and asked when our next planetary launch would be. I explained that it would occur in 13 months, AC-30 to Jupiter, and he said "You've got 13 months to find a better way to fly through the winds." Clearly, we had precious little time to find some other, drastically different, approach.

TABLE 1.—BOOSTER STEERING PROGRAM EVOLUTION

Dates	No. of vehicles	Centaur Booster	Type of Booster Steering
1962 to 1966	9	Atlas	Seasonal pitch programs (4)
1967 to 1972	18	Atlas	Predefined launch day-selectable pitch and yaw programs (10 pitch and 10 yaw)
1972 ^a	1	Atlas	Predefined launch day-selectable pitch and yaw programs (10,000 pitch and yaw combinations)
1973 to 2006	>100	Atlas	Launch-day-designed pitch and yaw programs (ADDJUST)
	8	Titan	

^a Scrubbed 3 days for winds!!

4.0 ADDJUST Development

Immediately after the AC-27 launch, Lewis management asked Mr. Jack Estes and me to co-lead the ADDJUST activity for Lewis. We went to out to GD, in San Diego, who then appointed about a six person team headed by Mr. Daniel Swanson, who authored the initial, brief paper on ADDJUST (Ref. 1). It was clear that the new approach had to design a pitch program and yaw program tailored to the wind measured on launch day, as opposed to searching for a preprogrammed combination designed for some simplified, synthetic wind profile. The first breakthrough idea was that, unlike former programs which were pitch and yaw rate versus time, we needed to design the new program as attitude versus altitude. The wind profile is measured as speed and direction versus altitude, not time of flight. This approach eliminated variations resulting from booster thrust dispersions, i.e., it eliminated uncertainties in the time the vehicle achieved a particular altitude. If no wind were simulated, a trajectory design produced a vehicle attitude history (or profile) resulting in zero angle of attack. To achieve zero angle of attack when non-zero winds were considered, the resulting attitude history for zero angle of attack varied slightly, or be “biased” from the zero wind attitude profile. Much of the following technical data in this section was resident (or implicit) in the “Countdown Summary, Launch/Hold Criteria, and Flight Events” document GD prepared each launch (Ref. 4).

4.1 Wind Filtering

First we needed to measure the wind profile, and then resolve it into pitch and yaw component profiles, depending on the launch azimuth (Figure 3). Then we had to apply some kind of filter to the pitch and yaw profiles separately. The wind had to be smoothed, or filtered, to avoid designing or “tuning” to exactly the real measured wind because the high frequency

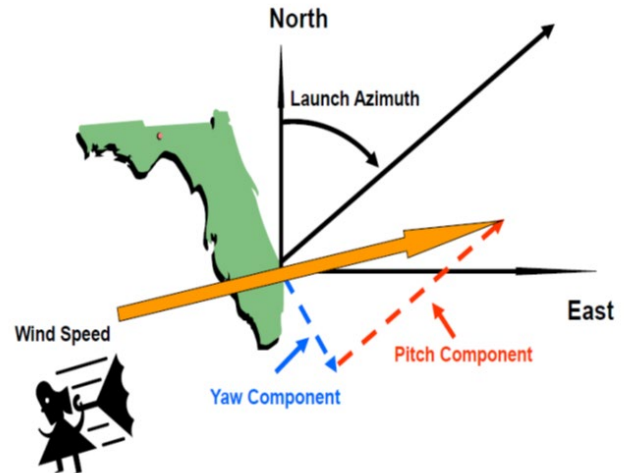


Figure 3.—Pitch and Yaw Components of Wind Velocity Vector.

wind characteristics would no longer be present by the time the vehicle ascended to the critical altitudes (typically 30,000 to 50,000 ft, and about 2 hr after the measurement was taken by balloons. See Sec. 4.6). If the filter smoothed the wind too much, however, it would approach the case of the ill-tuned synthetic winds which were incapable of producing acceptable launch availability. Finding the proper amount of smoothing was critical. We would then design the trajectory profiles to the filtered, or smoothed, wind. Later, of course, we had to fly the resulting ADDJUST pitch and yaw profile through the real wind to verify all mission critical parameters.

After considerable trial and error and judgment by team members experienced in analyzing wind profiles, we employed a running average technique which eliminated high frequency wind components in the creation of a “filtered,” or “design,” wind. For the vertical rise phase, 0 to 1,200 ft, there was no filtering. From 1,200 to 8,000 ft, the trajectory was designed for overall trajectory shaping, i.e., this interval shaped the trajectory to meet the mission orbital requirements, e.g. earth orbital, lunar, planetary, etc. The ADDJUST “biasing” of the required attitude history was just a small dither or “adjustment” (or is it ADDJUSTMENT?) which could be applied to any overall mission shaping. It was critical that the overall mission trajectory shape be calculated first, and then ADDJUST applied to reduce the angle of attack. The pitch profile was designed to achieve the proper integrated heating (mission dependent) at booster engine cutoff (BECO), and the velocity heading in yaw was designed to be the same as if no yaw were performed. This was accomplished by a simple 2X2 iteration, i.e., iterate on initial pitch attitude at the beginning of this altitude segment to hit the right integrated heating, and on the initial yaw attitude to yield the proper yaw heading at BECO. This iteration with two control variables and two end conditions had to be kept simple to

ensure convergence on launch day (see Figure 4 and Figure 5). We were always concerned about whether ADDJUST would converge—but it always did.

Since there were no wind concerns in this interval (slow speed, low dynamic pressure), there was no wind filtering, and the trajectory was not yet designed for zero angle of attack. The third phase was designed to minimize pitch and yaw angles of attack and resultant air loads through booster engine cutoff (BECO). In this phase, between 8,000 and 16,000 ft, we represented the filtered wind by linear segments between averaged values at 8,000, 12,000, and 16,000 ft. The raw wind data was measured at 200 ft intervals. Any residual angle of attack at

8,000 ft was forced to decay to zero over the next 10 sec to ensure smooth vehicle responses. At every 200 ft altitude increment above 16,000 ft, we averaged the wind speed data over an interval of 6,000 ft. Measured wind data usually ended at about 60,000 ft, so from 60,000 to 80,000 ft, if we had no wind data, we linearly extrapolated to zero wind speed at 80,000 ft and above. The “filtered” wind profile resulted from this process. The above phases of flight were flown “open loop”, i.e., only the Atlas autopilot was in control. The Centaur guidance loop was not closed until BECO + 8 sec. A conceptual filtered wind is shown in Figure 6. A real filtered wind in pitch is shown in Figure 7.

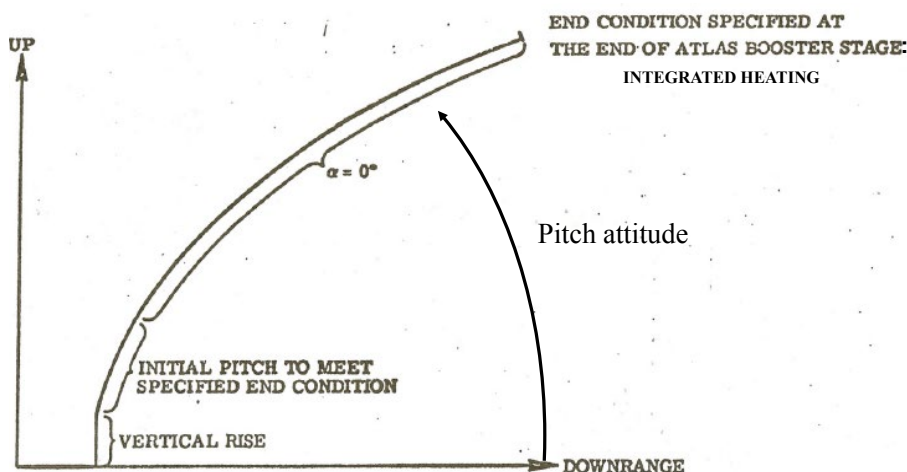


Figure 4.—Pitch Trajectory Shaping.

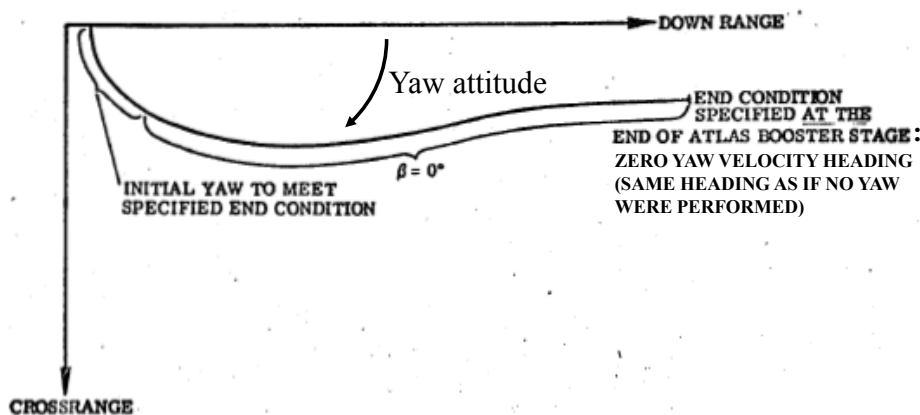


Figure 5.—Yaw Trajectory Shaping.

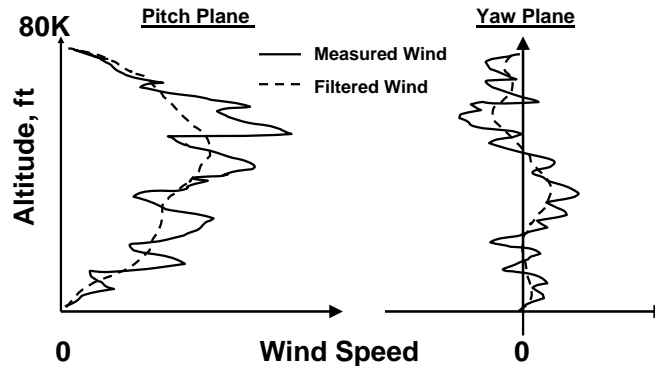


Figure 6.—Pitch and Yaw Wind Profiles Versus Altitude.

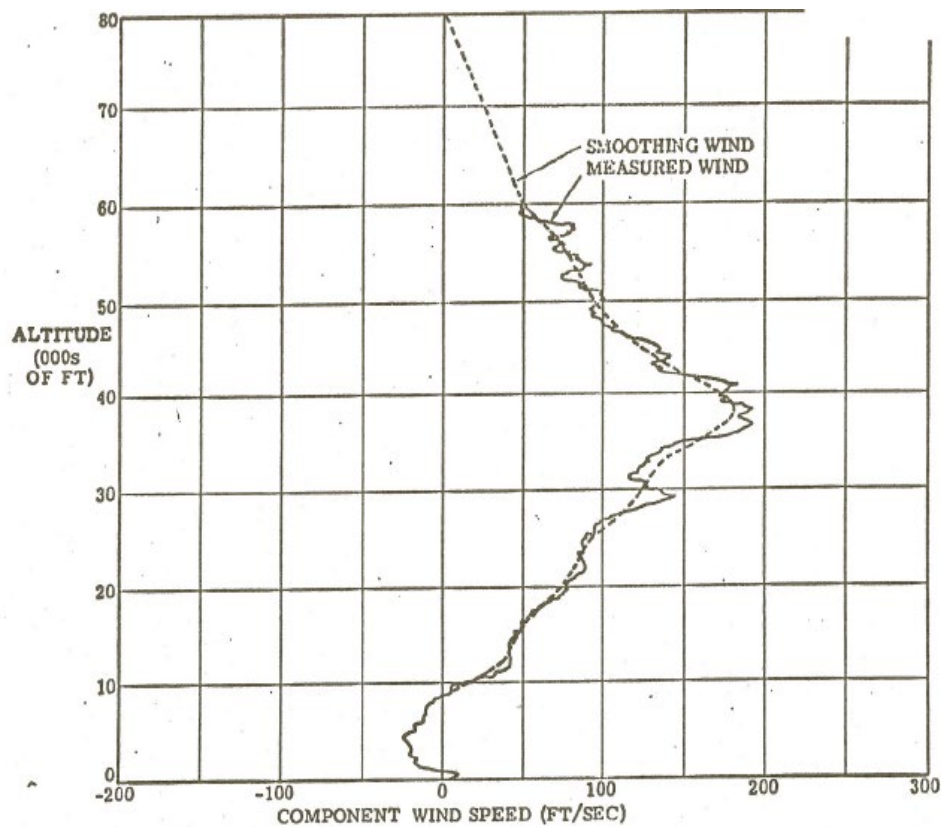


Figure 7.—Example of Real Filtered Wind in Pitch Plane.

4.2 Altitude Segments

The next task was to break the altitude span into intervals, or “segments”. Over each interval, the filtered wind zero angle of attack history would be calculated, and then approximated with a polynomial fit. At first we tried linear fits, but the residual angles of attack were too large. Then we tried a second order polynomial, which reduced the residual angles of attack substantially, i.e., it gave a much better fit. When we tried third order fits, there was little improvement over the second order,

so we decided to use second order polynomials over each interval because they were simpler and had fewer coefficients to be transmitted. Two second order polynomials, one in pitch and one in yaw, were used to define the desired vehicle attitude over each of 11 preselected altitude segments. The altitude intervals selected for segmentation varied. The shortest interval was 5,000 ft over the 30,000 to 50,000 ft altitude range where dynamic pressures were high and could induce large angles of attack and high loads. The coefficients of the polynomials were called “steering terms.” The routine that designed the steering

terms was called “Pipeline”. Table 2 illustrates the intervals. Figure 8 illustrates the zero angle of attack profile as approximated by polynomials. Note that the polynomials were attitude versus altitude, not rate versus time as mentioned earlier. Actually, we used “relative altitude”, which zeroed at the start of each altitude segment, and we required attitude continuity at the beginning of each segment (Figure 9). This approach required only 66 coefficients (11 segments, with constant, linear, and quadratic coefficients for each, both pitch and yaw) or “steering terms,” to be loaded into the flight computer, and verified for transmission accuracy. We tried very hard to keep the number of coefficients to a minimum because of the significant concern about transmitting flight critical constants to the flight computer very near (sometimes only a few minutes) before launch. We went through exhaustive testing to absolutely prove our ability to do this repeatedly and reliably through the use of check sums, check figures, and parody checks. All the coefficients were checked prior to upload into the flight computer, and then downloaded again to verify accuracy.

Since the first use of ADDJUST was on AC-30, Pioneer 11 to Jupiter, a NASA Ames Research Center payload, Hans Mark, Ames Center Director, asked the Lewis Director, Bruce Lundin, for an all-day briefing on this thing called “ADDJUST.” Jack Estes and I had agreed from the start that, although we had different backgrounds and responsibilities for ADDJUST, we would both learn every aspect of the program. This turned out to be fortunate for me, since Dr. Mark wanted the briefing on a day which Jack was not available. After conducting an ~ 8 hr grilling (down to details, such as why we used a second order

polynomial fit), Dr. Mark returned to Ames very satisfied and confident in ADDJUST. (In about 1978, the Space Transportation System (STS) program also came to Lewis to understand how ADDJUST worked. They were very uneasy with transmitting critical data to the flight computer so close to launch, so they elected not to incorporate such a “risky” technique. But only a few years into the program, they also started to scrub for flight winds, so they eventually, reluctantly adopted a similar approach.) Typical coefficients are shown in Table 3.

TABLE 2.—ADDJUST PIPELINE ALTITUDE SEGMENTS
[11 segmented polynomials (pitch^a and yaw^b)]

Range of altitudes, ft	Set number of polynomial steering terms	Description
0 to 1,200	-----	Vertical rise after liftoff
1,200 to 8,000	1 st	Trajectory shaping (control section)
8,000 to 16,000	2 nd	Zero angle of attack phases
16,000 to 24,000	3 rd	
24,000 to 30,000	4 th	
30,000 to 35,000	5 th	
35,000 to 40,000	6 th	
40,000 to 45,000	7 th	
45,000 to 50,000	8 th	
50,000 to 60,000	9 th	
60,000 to 80,000	10 th	
80,000 and beyond	11 th	

$$^a\theta_p = P0(I) + P1(I) \Delta h + P2(I) \Delta h^2$$

$$^b\theta_y = Y0(I) + Y1(I) \Delta h + Y2(I) \Delta h^2$$

TABLE 3.—SET OF TYPICAL ADDJUST PITCH AND YAW POLYNOMIAL COEFFICIENTS

66
Steering
Terms

P2(1)= .167216E-08, .694523E-09, .576348E-09, -.597307E-10,
P2(5)= .860086E-09, .487614E-09, -.149315E-08, .381920E-09,
P2(9)= .151401E-09, .561135E-10, .141174E-10,
P1(1)= -.383397E-04, -.229257E-04, -.241354E-04, -.121632E-04,
P1(5)= -.151926E-04, -.543502E-05, .997671E-07, -.159500E-04,
P1(9)= -.107206E-04, -.720310E-05, -.397298E-05,
P0(1)= .157080E+01, .138145E+01, .124249E+01, .108630E+01,
P0(5)= .101117E+01, .956704E+00, .941720E+00, .904890E+00,
P0(9)= .834688E+00, .742621E+00, .621005E+00,
Y2(1)= .320677E-09, -.979688E-09, .489582E-09, -.939114E-12,
Y2(5)= -.823727E-10, -.180899E-09, .444163E-09, .746429E-10,
Y2(9)= .904295E-10, .150538E-10, .987045E-13,
Y1(1)= -.309715E-05, .948519E-05, -.379865E-05, .809960E-06,
Y1(5)= .902646E-06, .780545E-07, -.414202E-05, -.552969E-06,
Y1(9)= -.679641E-06, -.452725E-06, -.174775E-07,
Y0(1)= .000000E+00, -.561180E-02, .756970E-02, .851373E-02,
Y0(5)= .133397E-01, .157936E-01, .116614E-01, .205538E-02,
Y0(9)= .115661E-02, .340314E-02, .370152E-03.

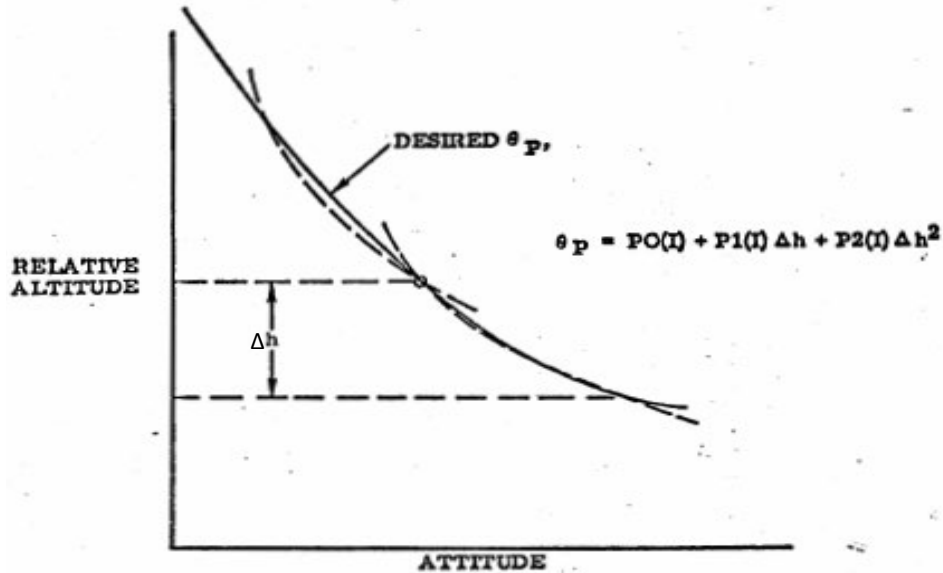


Figure 8.—Pipeline's Polynomial Fit Technique.

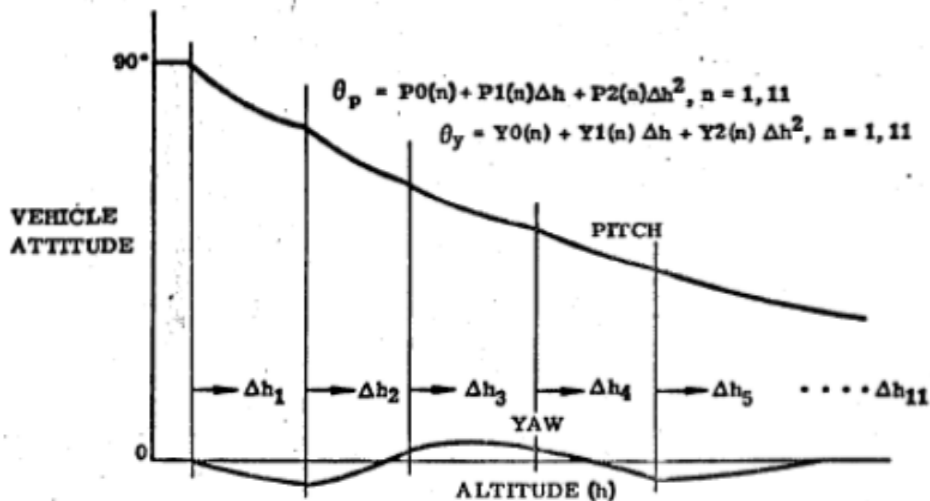


Figure 9.—Polynomials Versus Relative Altitude

4.3 The Wind Monitoring Process

The wind monitoring and ADDJUST processes are summarized in Figure 10 and Figure 11. The cycle, which was repeated several times on launch day, began with the release of a weather balloon, or usually a pair of balloons, by the U.S. Air Force weather team in Florida. These balloons returned wind speed and direction data as a function of altitude, as well as atmospheric properties. The wind profiles were transmitted to GD

in San Diego, and Lewis in Cleveland, for analysis. The zero angle of attack profile and the associated polynomial steering coefficients were calculated in San Diego by the ADDJUST program. These coefficients were then sent to Cleveland for verification and simultaneously to the Centaur ground computer at Launch Complex 36 for potential loading into the flight computer at a later time. The ADDJUST operational process is shown in Figure 11.

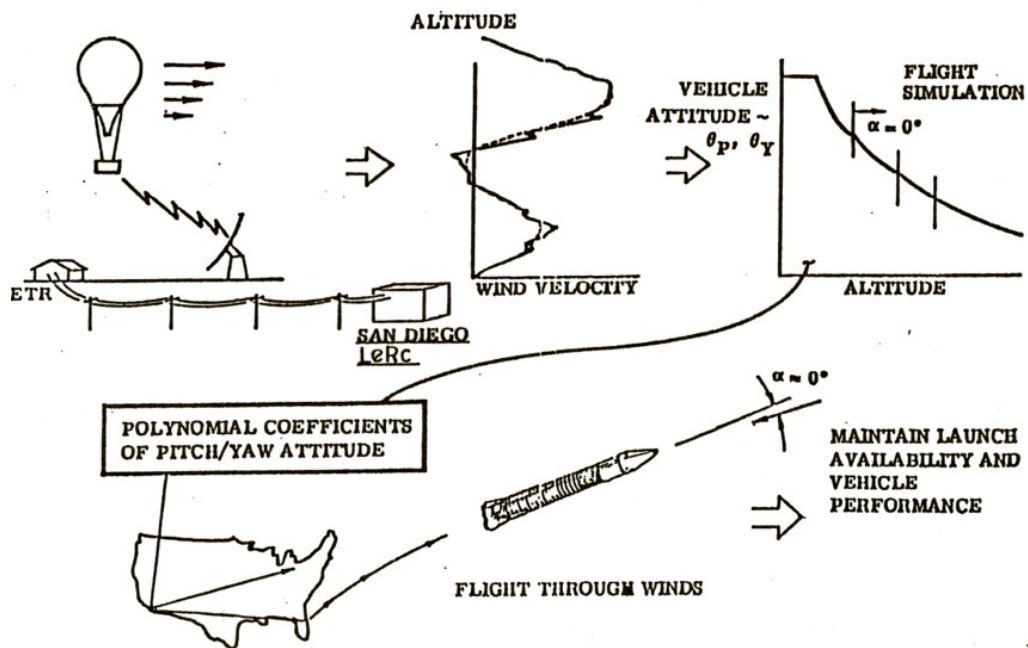


Figure 10.—ADDJUST Winds Monitoring.

Approximately 1 hour

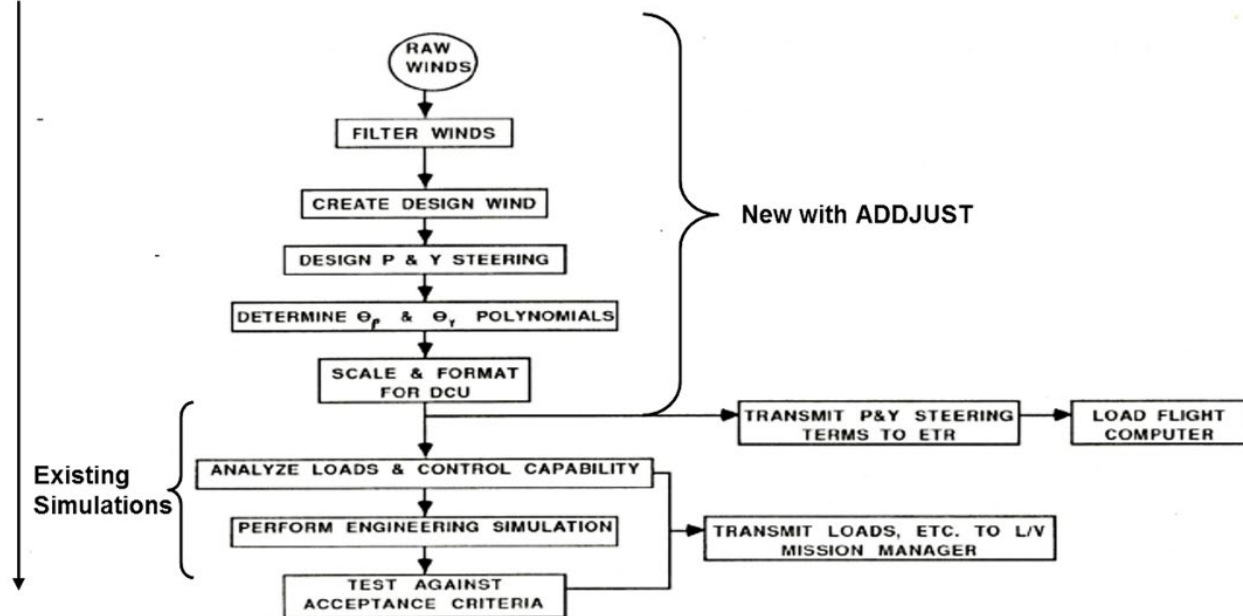


Figure 11.—ADDJUST Operational Process.

ADJUST started with the raw, unfiltered wind profile, and then ran the data through filters explained earlier. The filtered, or “design” wind was then used to calculate the zero angle of attack trajectory, the polynomial approximations for each altitude segment, and polynomial coefficients for both pitch and yaw planes. These 66 coefficients (called P ’s and Y ’s) were then scaled properly for the Centaur Digital Flight Computer (DCU), transmitted to the Centaur ground computer at Complex 36, and then uploaded to the flight computer if required. They were also sent to NASA Cleveland for subsequent validation. We were always very aware of the potential for transmission errors in this process, so we took great precautions to make sure the data was sent correctly through the use of check figures, check sums, and parity checks, similar to verifying the flight computer loading as described earlier. I don’t recall ever having problems with transmission errors, although we had frequent problems with losing the phone lines from Florida to Cleveland and to San Diego. All the data was sent over phone lines. At first, we had to use government lines, which were plagued with problems. Soon, we said that we needed to use more reliable commercial grade lines, at a transmission rate of 300 baud. (One person commented that transmission was so slow it was almost possible to see the bits coming out of the phone receiver!) When we went to commercial lines, the phone company warned us that if we ever tried to launch on Mother’s day, we may not be able to get a line. I don’t recall that we ever launched on Mother’s day.

All of this activity was coordinated by Lewis personnel in the tiny “Wind Room” behind the Launch Complex 36 Mission Director’s Center in Hanger AE.

Once the P ’s and Y ’s and the actual, measured wind profile (not the filtered wind) were loaded into the 6 degree of freedom (6 DOF) simulations in San Diego and Cleveland, then the process of computing the resulting loads, control authority, and many other mission parameters took place, including automated comparison with predetermined allowables for each. This whole process took about 1 hr. Since the balloons needed an hour to reach the correct altitude in the first place (typically around 60,000 ft, if they didn’t burst, freeze up, or blow over the horizon first), this meant the measured wind was about 2 hr old by the time the vehicle flew through it. We examined using laser and/or Doppler scans in lieu of balloons because they were nearly instantaneous, but because of technical issues, we stayed with balloons. This is still true today for Atlas V.

4.4 Mission Acceptance Criteria

Even though successfully negotiating the flight winds was absolutely critical, as mentioned earlier, ADJUST also

verified that all equally critical trajectory criteria were met to ensure mission success:

- Structural loads
- Control capability
- Nose fairing temperatures
- Angles of attack, pitch and yaw
- Integrated heating
- Product of dynamic pressure and angle of attack (Q-Alpha) and sideslip (Q-Beta) at jettison events
- Angular rates and accelerations, pitch and yaw
- Performance to Centaur target orbit
- Range safety boundaries

Trajectories resulting from each ADJUST design were appropriately scaled and transmitted directly to Range Safety at the Eastern Test Range (ETR) for immediate display for the Range Safety Officer. Initially, the displays were pen on paper. Later they became cathode ray tube (CRT) based. None of these constraints was ever violated by any ADJUST simulations on launch day.

4.5 Loads Overview

Loads during maximum aerodynamic loading region (typically 30,000 to 50,000 ft) were caused by:

- Steady winds, which were a function of trajectory and wind profile
- Axial acceleration
- Drag, which was a function of trajectory shaping and wind profile
- Gusts, which were short term wind changes not included in the wind profile
- Wind persistence, the variation in wind profile as a function of time
- Buffett, which was treated like random loads
- Dispersions, some of which were variations in wind measurements, trajectory, propulsion system, mass properties, and aerodynamics

In the above list, the first three had to be calculated on launch day using predetermined coefficients. The last four could have been calculated well in advance of launch day. A 1976 study led to updated criteria for gust, persistence, and dispersion loads, and this was implemented and used for updated Atlas/Centaur flight wind monitoring criteria. Structural factors of safety are shown in Table 4. These safety factors were intended to account for the inability of analysts to perfectly

TABLE 4.—ADJUST FACTORS OF SAFETY AND OTHER CRITERIA

Vehicle	Station (Centaur)	Time (seconds after T = 0)	Ultimate factor of safety		Buckling criteria at limit load	Buckling criteria at ultimate load
			Axial load	Bending moment		
Centaur (tank skin)	219 to 409	0-100	1.10	1.25	Onset	180
Centaur (rings)	219 and 412	0-100	1.10	1.25	None	None
N/F	All	0-100	1.10	1.25	None	None
Atlas (tank skins)	674 to 819	0-100	1.10	1.25	Onset	180

calculate loads, load paths, strengths, etc., or for overly simplified analytical techniques.

ADJUST calculated two ratios which were used as principle criteria for launch. The Capability Ratio (CR) was a modification of the stress design-limit interaction ratio and was the sum of two quotients: the applied-to-limit bending moments with zero axial load; and the applied-to-limit axial load with zero bending moment. It was evaluated at various critical stations along the length of the launch vehicle. The Engine Ratio (ER) was the ratio of predicted-to-allowable engine gimbal angle for the Atlas booster engines.

CR and ER were calculated at each time for each vehicle longitudinal location, or station. For historical perspective, it should be noted that whether the CR or ER was the predominant constraint was very vehicle dependent. For example, for the Atlas/Centaur the CR was always the constraint, but for Thor/Agena the ER was always more critical.

The highest CR or ER encountered at any time or station was used in the above calculation for “GO” or “NO-GO” CR ≤ 1.0 and ER ≤ 1.0 are required for a launch “GO.”

4.6 Wind Persistence

The wind the vehicle actually encountered in flight was not identical to any wind previously analyzed. It would have changed even relative to the wind measured as close to launch as possible. Even small wind changes could have induced significant pitch and/or yaw loads. This inevitable change had to be addressed with a “persistence allowance.” The nominal launch day balloon release schedule is shown in Table 5. The day before launch, the first pair of balloons (the System Check balloons (Ref. 3), not shown in Table 5) was launched primarily to verify readiness of the entire balloon release and ADJUST system. On launch day, four pairs of balloons were released per the schedule. The reserve balloons were released primarily to rehearse the system for later in the day. ADJUST designed to each pair, but the design was not loaded into the flight

TABLE 5.—LAUNCH DAY BALLOON RELEASE SCHEDULE

Ballon pair	Release time, min	Pitch and yaw steering design
Reserve	L-370	Yes
Secondary	L-265	Yes ^a
Primary	L-145	Yes ^a
Contingency	L-90	No ^b

^a Loaded into flight computer

^b Except on hold

computer. The secondary and primary designs were loaded. The contingency data was not loaded unless we were in a launch delay, and it was used to assess the projected CR/ER increase for extending the launch into a protracted window. The window would close when the CR or ER were calculated to exceed a value of 1.0. (See discussion below). The contingency data were also used for post flight analysis purposes. As an example, Figure 12 and Figure 13 show the smoothed wind and measured wind for the same launch day, March 26, 1987, both in pitch and yaw, for the secondary and contingency balloons.

The structural capability ratio, CR, was always the most critical factor for Atlas/Centaur (see Sec. 4.5), i.e., it was the parameter always closest to its limit, and the factor on which a launch “Go/No Go” was based. We needed to calculate a “persistence allowance” for the CR. That is, statistically, how much should we allow for the CR to rise to account for the fact that our last measurement, based on the primary balloon sounding, would be more than 2 hr old by the time the vehicle actually flew through the wind? We initially analyzed 150 historical balloon pairs released from ETR from 1965 to 1972, and released about 2 hr apart to approximate the launch day time lag discussed above. We designed an ADJUST profile for the first balloon in the pair, and then analytically flew that profile against the second balloon data to see how much the CR had changed. We also analyzed numerous wind pairs that had actually caused past launch delays. Had ADJUST been available, all would have been “GO.” Finally, we examined synthetic wind pairs and other profiles specifically designed to “stress” the system. Each time, we executed a complete ADJUST design cycle for the first balloon of the pair and calculated the CR, as well as all the other mission acceptance criteria. Using the ADJUST profile designed for the first balloon, we flew this profile against the second balloon’s measured wind profile and again calculated the CR and all other parameters, noting the changes from the first balloon results. We then performed a statistical analysis on the resulting distribution of the changes and calculated a 3 sigma value for changes in CR and ER. This resulted in a CR persistence allowance of about 0.06/hr, or six “points/hr” (highly vehicle dependent). This factor was also

used to predict when an extended launch window would close based on expected CR/ER limits. If the window were long enough, a balloon pair later than the contingency pair would be launched. Results showed that the average increase in calculated loads for ADDJUST cases was about what had been

experienced in the past for predesigned (i.e., non ADDJUST) steering terms. This indicated that ADDJUST design was not overly sensitive to lack of wind persistence. Historically, for Atlas/Centaur, CR was always much more critical than ER. In fact, for that vehicle it was always the most critical parameter.

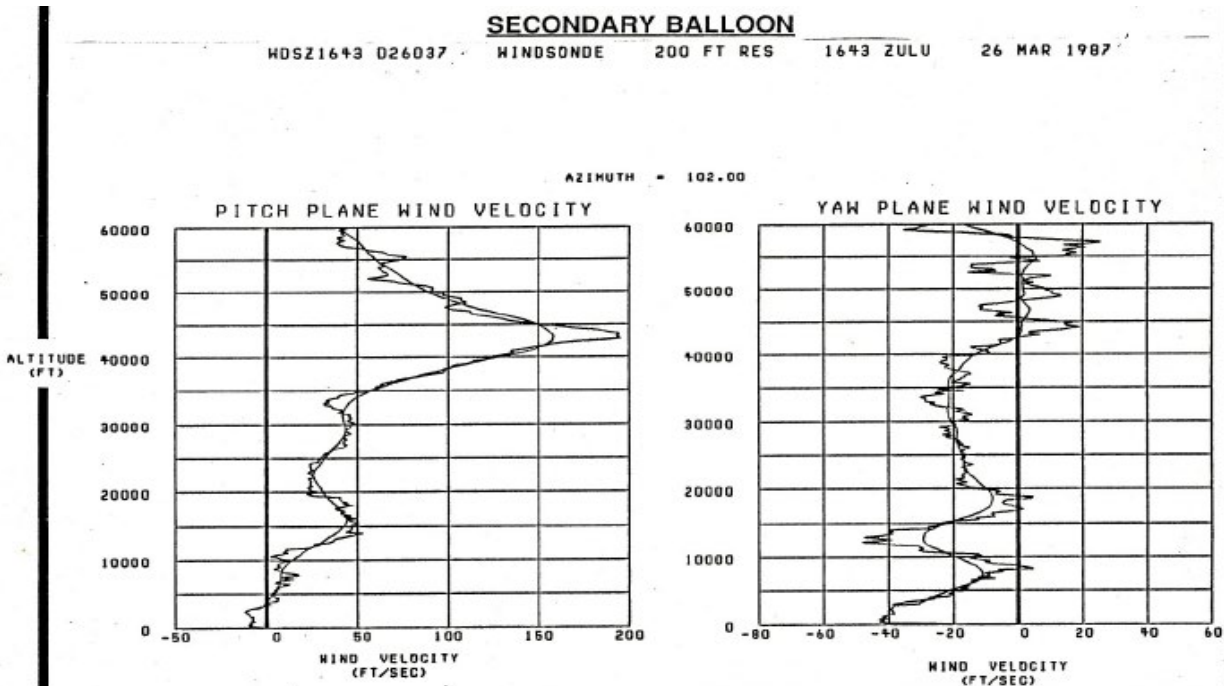


Figure 12.—Secondary Balloon Wind Profiles.

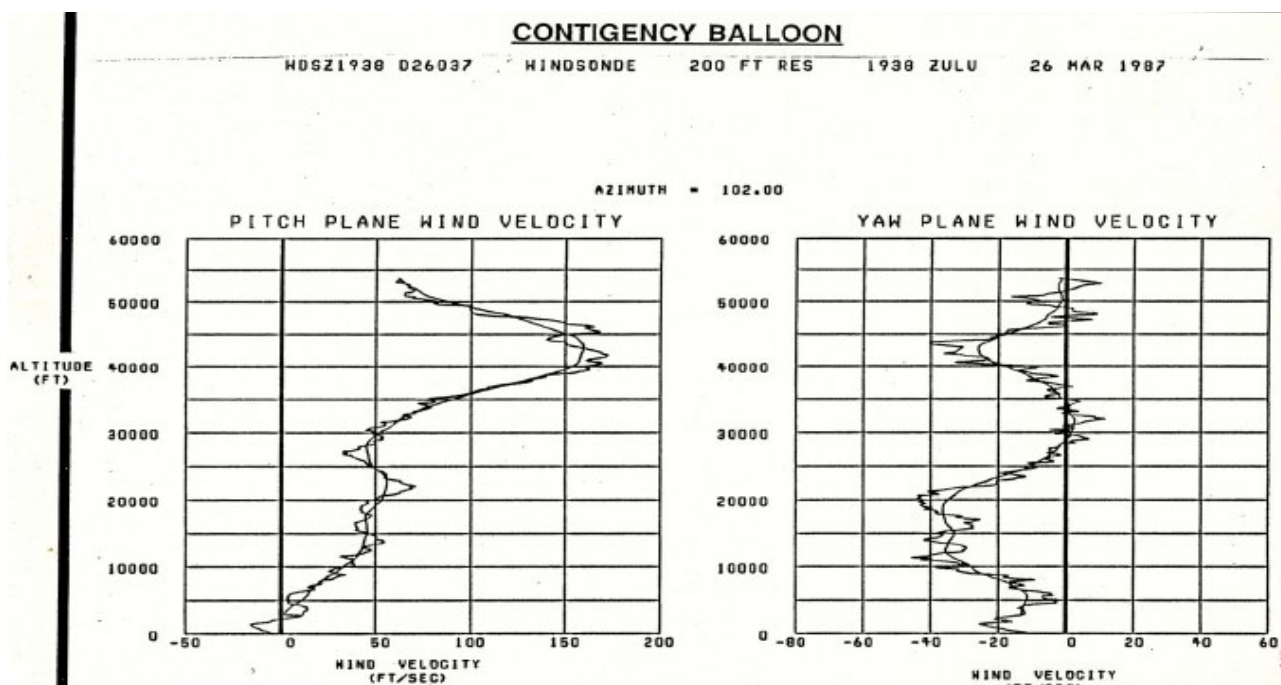


Figure 13.—Contingency Balloon Wind Profiles.

4.7 NASA Lewis Independent Verification And Validation

The primary purpose of the Lewis IV&V was to independently calculate and verify all the mission acceptance criteria (i.e., CR, ER, performance, range safety, etc.). We ran in-house 3D and 6D simulations, completely independent from GD. Because of extensive (over many years) prelaunch simulation comparison and calibration, Lewis and GD would always agree to within 0.01 (1 “point”) on CR. If either capability went down on launch day, the other could issue the “GO” or “NO GO.” The decision was always “NO GO” if either exceeded 1.0. To accommodate ADDJUST and its potentially very compressed time frames if we were late in the countdown, Lewis undertook a major upgrade in its IV&V hardware and software capabilities for data processing and analysis. We did not independently calculate the ADDJUST steering terms, although that could have been done. It was not a priority.

While GD calculated ADDJUST steering terms, Lewis first ran the previous ADDJUST design through the current, measured wind. Next, we ran the current wind through the backup matrix of 10 pitch and 10 yaw programs, searching for a “GO” set (after 1972, we rarely found one). This effort was valuable because the backup sets also resided in the Centaur ground computer at Launch Complex 36 and were not subject to potential cross-country data transmission breakdowns. As it turned out, these communications breakdowns were actually infrequent and they never prevented us from eventually

transmitting the coefficients. We never needed a backup choice with ADDJUST. Lastly, Lewis validated the current ADDJUST design through the current wind.

4.8 Flight-Measured Angle of Attack

The next several charts (Figure 14, Figure 15, and Figure 16) present the flight-measured angle of attack data for three flights, as measured by a differential pressure sensor on the nose cap. Each set shows the angle of attack history for the critical period of flight for pitch and yaw (P and Y), and the root sum square (RSS) of the two. The first set was for AC-26, launched on December 19, 1971. The solution was selected from 10 predesigned P and Y steering sets. The RSS of P and Y angles of attack are about 2.0° . Not great, but good enough for a “GO.” The second set was for AC-27, launched on March 2, 1972. The solution for this flight was selected from 10,000 predesigned P and Y steering sets. The RSS of P and Y angles of attack are between 1.5° to 2.0° . This was good enough for a “GO,” but we had scrubbed for three previous days because the prelaunch search for a solution was too complicated and took too long. This was the flight that led to the birth of ADDJUST. The last set was for AC-30, launched on April 5, 1973. This was the first use of ADDJUST. The charts show the best match yet for zero angles of attack in both pitch and yaw, with an RSS of about 0.5° , resulting in a “GO” on the first attempt. This reduced angle of attack led directly to improved launch availability.

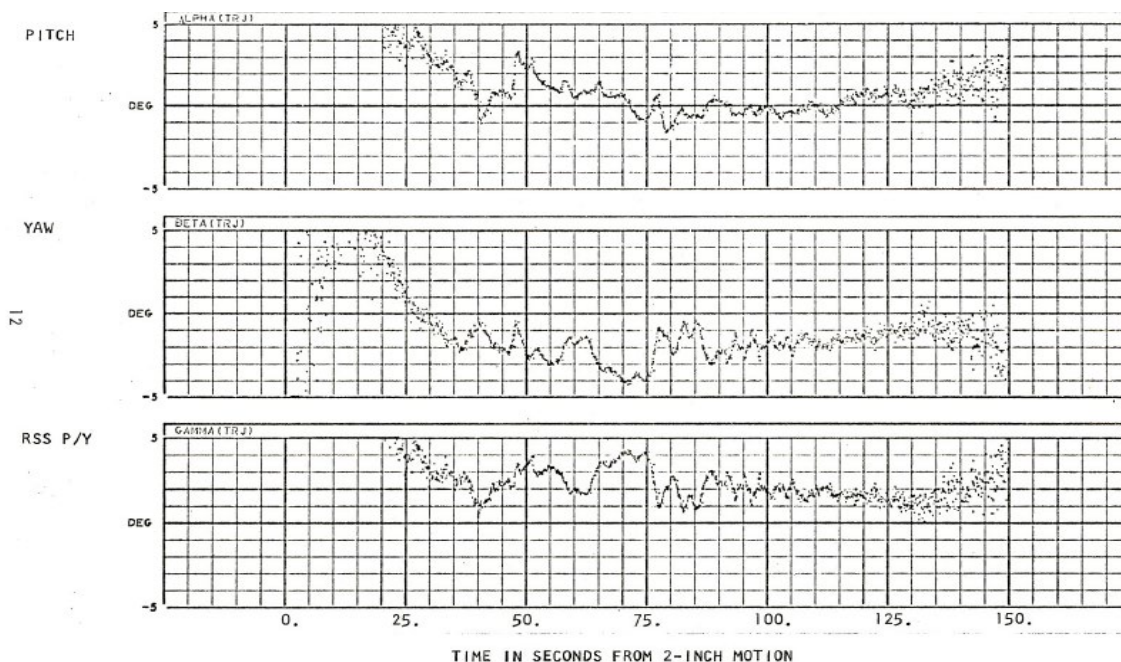


Figure 14.—AC-26 Flight Angle of Attack (No ADDJUST)

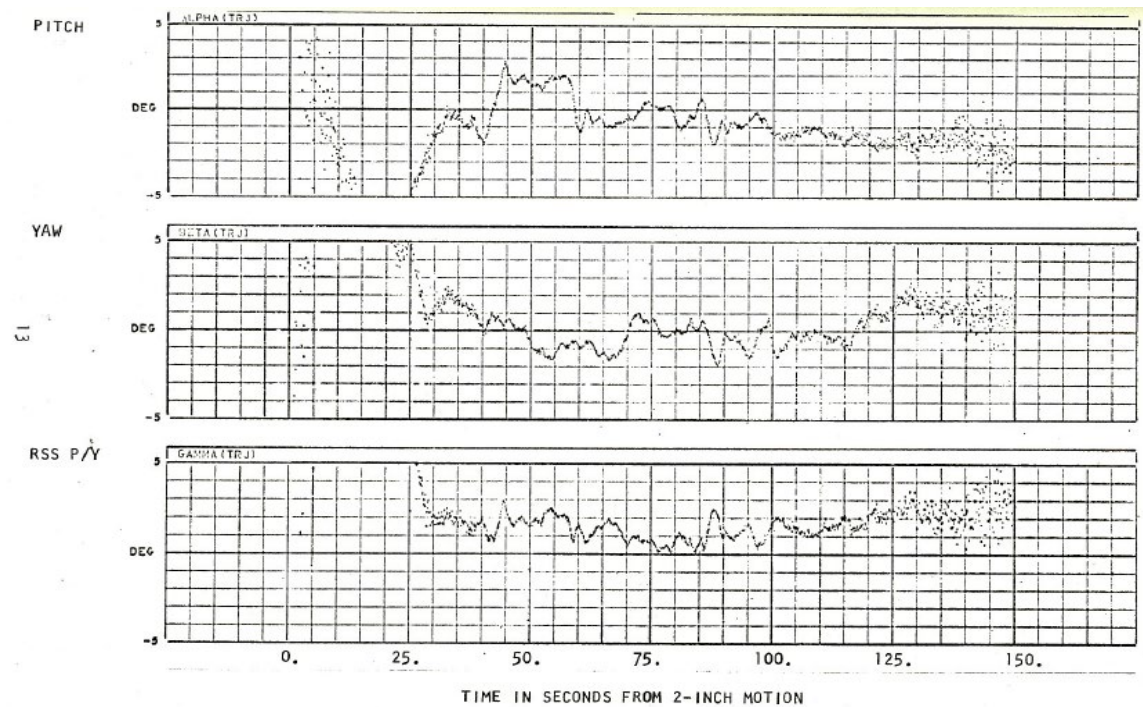


Figure 15.—AC-27 Flight Angle of Attack (No ADDJUST).

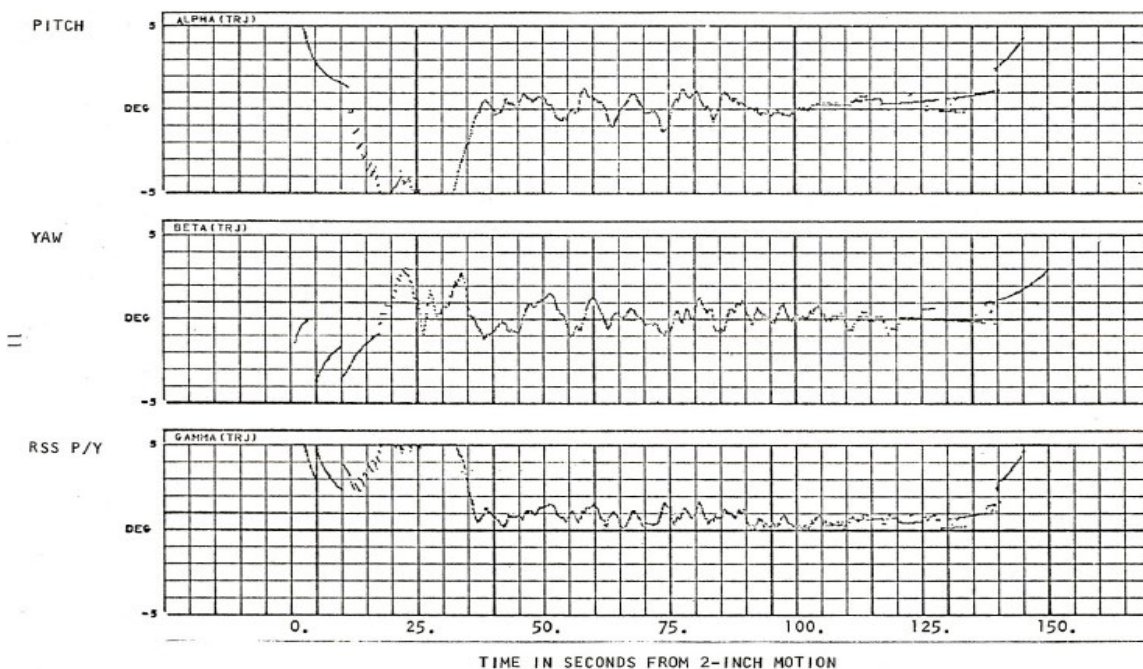


Figure 16.—AC-30 Flight Angle of Attack (First ADDJUST Usage)

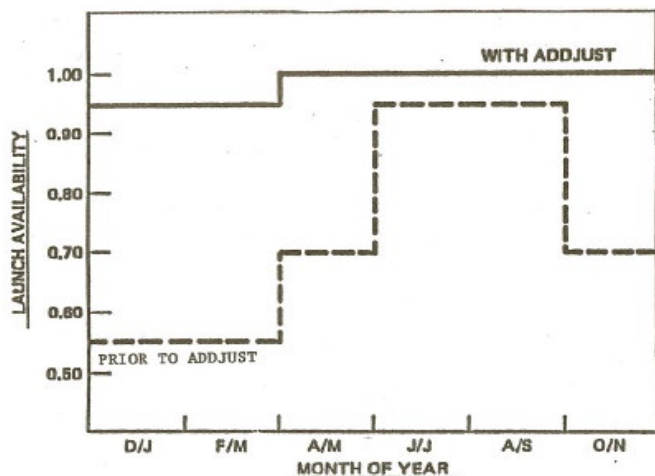


Figure 17.—Launch Availability Improvement with ADDJUST.

4.9 Launch Availability

Launch availability is the percentage of days in a year (expressed as a decimal) for which prelaunch analyses predict a “GO” for flight winds (i.e., launch availability of 0.9 meant a predicted “GO” for 90 percent of days). Frequently, launch availability is calculated for each month. The goal of ADDJUST was to yield a launch availability in the winter months of at least 90 percent. The resulting launch availability is shown in Figure 17. As can be seen, where the winter months previously had yielded a launch availability of only 55 percent, with ADDJUST it went to nearly 100 percent.

The ADDJUST system cost about \$250,000 to develop. In return, it saved countless scrubs at more than \$1 million per day. Including its first use on AC-30, ADDJUST flew on 44 Atlas/Centaur and 7 Titan IIIE/Centaur flights through 1998. *Even allowing for persistence, ADDJUST always found a solution on the very first attempt. Through the end of the Centaur program at Lewis in 1998, we never scrubbed for flight winds again!*

5.0 Conclusions

ADDJUST was the first use of steering programs derived and uploaded in near real time, and it met or exceeded every one of its design goals. It is a remarkable achievement and set the standard for near real time, reliable communications of flight critical software. It prevented countless scrubs due to flight winds, avoiding the associated risks. ADDJUST was flown on 51 Centaur flights from 1973 until 1998, and always enabled a “GO” on the very first attempt, resulting in a year round launch availability of nearly 100 percent. In this period, we never scrubbed for flight winds again. Even its acronym (conceived by Frank Anthony of GD) was remarkable, and remains one of the most ingenious and descriptive ones I can recall. Participating in its development was one of the highlights of my career. Working with Jack Estes at Lewis, and with Dan Swanson and his dedicated team at GD, showed me what a small, highly motivated team could accomplish, even with a very short schedule and extreme pressure to produce. I always felt that it was an honor to be asked to work with these fine gentlemen.

Reference

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4. “Countdown Summary, Launch/Hold Criteria, and Flight Events, CRRES Mission, AC-69,” General Dynamics Commercial Launch Services, Report No. GDSS-ACE-87-001, Contract NAS3-23330, San Diego, CA, July 1990.

